

**DESIGN OF A SWITCHED-RELUCTANCE MOTOR DRIVE  
FOR ELECTRIC PROPULSION**

Research Project 98PR05665 – 00  
Period of Performance: May 01, 1998 – April 30, 2001

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**First Annual Report (AR1)**

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## **Introduction**

This First Annual Report summarizes the activities performed on this grant from August 1, 1998, until April 30, 1999. Detailed technical reports will be written once that a specific topic or task has been completed; for example, refer to reference [1].

We were informed by late March 1998 (i.e., approximately the middle of the spring 1998 semester) that the Office of Naval Research decided to fund our grant with a starting date of May 1, 1998. We assembled the research team by August 1998 since we were able to hire all graduate students by the fall 1998 semester. Graduate students normally start their graduate studies in the fall semester (that normally begins around mid August) or in the spring semester (that normally begins around mid January). Also, it normally takes 2 to 3 months to find graduate students qualified for a specific research project. We are expecting to speed up our efforts so we can finish this research project by its ending date (i.e., April 30, 2001).

The remainder of this report addresses the assembled research team, the main activities performed during the period covered by this report, the activities in progress, and the expenses incurred from August 1, 1998, to May 15, 1999.

## **The Research Team**

The research team consists of 2 faculty members (J. C. Balda and T. W. Martin) and 4 graduate students (doctoral students E. Mitre Hall, S. Ramamurthy and Z. Z. Ye, and master student R. M. Schupbach). Mr. Mitre Hall and Mr. Ramamurthy are working on the design of two different Switched Reluctance Motors (SRMs) and Mr. Ye and Mr. Schupbach are working in the development of the controller and its associated power converter. Dr. Balda supervises the designs of the two SRMs and the power converter, and shares direction of the controller design with Dr. Martin.

## **Main Activities from August 1, 1998, to April 30, 1999**

The following technical activities have been performed:

- Sizing of the electric motor for the considered Electric Vehicle (EV).
- Analysis of different SRM topologies.
- Analysis of the power converter and the control task.

### *Sizing of the SRM for the considered EV*

The first technical task of this project determined the peak and continuous (or rated) power ratings of the SRM. The peak power rating was determined by taking into consideration the EV specifications including its acceleration time (or full "throttle" acceleration). Here, the limiting factor is the peak winding temperature. The continuous power rating of the electric motor is based on the thermal limits imposed by the driving cycles. We used the Federal Urban and Highway Driving Schedules (FUDS). Normally, the continuous power rating is between 25 and 50% of the peak power rating. Reference [1] provides the results of this task; it must be noted that a computer program called Ecar to determine the peak power rating of electric motors for electric propulsion applications was developed during this task.

In addition, we analyzed the main requirements for a electric motor drive used in EV applications. From this analysis, we determined the following:

### *Technical aspects of a SRM drive:*

Specify	Constraints
<ol style="list-style-type: none"> <li>1. Maximum and rated speeds</li> <li>2. Supply voltage</li> <li>3. Number of poles</li> <li>4. Vehicle driving schedules</li> <li>5. Maximum sudden-impact load.</li> <li>6. Materials available</li> <li>7. Temperature rise</li> <li>8. Ambient temperature</li> <li>9. Method of cooling</li> </ol>	<ol style="list-style-type: none"> <li>1. Battery limitations (e.g. maximum current and drawing rate).</li> <li>2. Protection requirements (e.g. short-circuit protection).</li> <li>3. Dimensional constraints</li> </ol>

Some of these aspects could place constraints on a SRM drive design or make a particular design more suitable than others.

#### Design goals for a SRM drive:

Minimize	Maximize	Achieve	Other Goals
<ol style="list-style-type: none"> <li>1. KVA</li> <li>2. Mass/Weight</li> <li>3. Noise level</li> </ol>	<ol style="list-style-type: none"> <li>1. Torque and power densities</li> <li>2. Efficiency</li> </ol>	Desired torque-speed (or road load) characteristic	Torque ripple minimization

Based on the above results, the research team established the subsystems where the different performance criteria might be better accomplished; the results of this analysis are shown below:

Goal	Motor	Converter	Control Approach
1. KVA minimization	⊕⊕⊕		⊕
2. Motor mass/weight minimization	⊕⊕⊕		
3. Motor dimensions	⊕⊕⊕		
4. Torque-Speed Characteristic	⊕⊕	⊕⊕	
5. Efficiency	⊕⊕	⊕	⊕
6. Noise level	⊕	⊕	⊕⊕
7. Torque ripple	⊕	⊕	⊕⊕

The symbol ⊕ indicates that the considered goal could be achieved within the design of the marked subsystem; a larger number indicates an advantage of the considered subsystem over the others.

#### Analysis of Different SRM Topologies

The team responsible for the design of the SRMs started to consider different SRM topologies proposed in the literature. A summary of the considered topologies is found in Table 1. From an analysis of this table, we can mention the following:

1. The self inductance is constant in the case of a SRM having full-pitch windings. Remember that torque in short-pitch SRM is produced by the variation of the winding inductance with the rotor position. Hence, torque production in a full-pitch SRM makes use of the mutual inductance between phases.
2. In the case of a SRM having fractional-pitch windings (FRSRM), the self inductances vary like in the case of a SRM having short-pitch windings.
3. A unipolar converter is required for the 6/2 and 6/4 SRMs.
4. A bipolar converter is required for the 10/8 SRM controlled under multi-phase excitation.
5. Either unipolar or bipolar excitation can be used for the 8/6 and 12/8 SRMs, even if multi-phase excitation is applied.
6. For the 12/8 FRSRM, three-phase bipolar converters should be used.

7. Additional torque improvement can be achieved for all cases by applying pole tapering. Preliminary results indicate that this contribution is not important.

Based on an analysis of the literature and the results from finite-element analysis performed on 6/2, 6/4, 8/6, 12/8 SRMs, we decided to optimize the designs of two different SRM drives in order to compare their performances. The design of the first SRM will consider a SRM having either short- or full-pitch windings and making use of multi-phase excitation.

Table 1 Considered SRM Topologies for Electric Propulsion.

 	Short-Pitch Winding	Full-Pitch Winding	Fractional Winding
6/2	Zero-torque region (dead zone), ∴ High-torque ripple and low average torque. Non-zero starting torque can be achieved at all rotor positions using stepped rotor pole construction.	Similar features as the 6/2 SRM with short-pitch winding. Better usage of electric circuit, ∴ Higher torque density than the 6/2 and 6/4 SRMs with short-pitch windings.	-
6/4	Only one phase produces torque at a time; this is the base case.	Higher torque density than short-pitch 6/4 SRM and full-pitch 6/2 SRM.	Better usage of electric and magnetic circuits, ∴ Increased torque density.
8/6	Two phases can produce torque simultaneously by multi-phase excitation. Using current profiling, increased torque density or zero torque ripple becomes possible.	New excitation technique being tried which will also make better use of magnetic circuit. Using current profiling, more torque density than the full-pitch 6/4 SRM or zero torque ripple becomes possible.	-
10/8	Two phases can produce torque at a time. Continuous operation in multi-phase excited mode becomes possible due to increased overlap between phases. Can apply current profiling.	New excitation technique being tried which will also make better use of magnetic circuit. Continuous multi-pole operation. Can apply current profiling.	-
12/8	Two phases start and end the overlap region together, ∴ Cannot apply current profiling. Continuous operation in multi-phase excited mode possible. This case is a replica of the 6/4 SRM.	Two poles start and end the overlap region simultaneously. Continuous multi-pole operation. Cannot apply current profiling. Replica of the 6/4 SRM.	Better usage of electric and magnetic circuits, ∴ Increased torque density.

The design of the second SRM will be based on a fractional-pitch SRM; this motor has the potential to produce approximately three times the torque of a short-pitch SRM operated under single-phase excitation. This torque increase could result in important weight and volume reductions. ANSYS is the finite-element software package used for the analysis of the different SRM topologies.

#### Analysis of the power converter and the control task

The team involved in the design of the power converter and its controller focused its research efforts on (a) designing a C-dump power converter and (b) establishing a suitable technique for modeling a SRM drive.

##### The C-dump power converter:

A power electronic converter is required in a SRM to:

- Provide a positive DC voltage to energize each phase winding when operating in the motoring mode, and
- Provide a zero or negative DC voltage to de-energize the phase winding (i.e., demagnetization) before the rotor pole reaches the aligned position; that is, the beginning of the generating mode. This stage is also called the commutation mode.

Although there are a large number of power-converter circuits, we considered three types of schemes; namely, the Asymmetric Half Bridge (AHB), the modified C-dump converter, and the two-level Voltage Source Inverter (VSI) typically used to drive induction machines.

The AHB has been widely used, especially in the 30-kW to 100-kW power ranges. It is considered to be simple, safe, and easy to control. In most cases, the switching devices are IGBTs that allow for higher rated voltages and currents as well as switching frequencies up to 50 kHz.

The modified C-dump converter is one of the best choices because of its faster demagnetization characteristics. This faster demagnetization allows fast transfer of energy out of the phase winding during the commutation mode when most of the torque ripple and acoustic noises are produced. Thus, the torque ripple and acoustic noise can be controlled or effectively reduced through the SRM control algorithm. In this converter, a faster demagnetization is obtained by dumping the energy from the phase winding into a DC capacitor before the aligned position is reached and before a negative DC link voltage is applied across the off-going phase. The energy trapped in the dump capacitor is utilized directly by the next on-going phase (rather than sent to the DC source) using a chopper operating as a buck converter. A C-dump power converter and feedback control for an 8/6 SRM has been design during the spring 1999 semester.

##### Modeling of SRM:

In order to achieve high performance, the SRM/converter system has to be optimized for a particular application (e.g., torque, speed, etc). Since a different design is needed for each different application, it is desirable to use a Computer Aided Design (CAD) tool to analyze different SRM designs and/or evaluate the impact of different converter topologies or control strategies. The CAD tool should:

- Accurately model the flux linkages and current of the phase winding, and the rotor displacement or position.
- Be computationally efficient.
- Generate the relevant performance parameters, such as time waveforms of  $\psi(t)$ ,  $i(t)$  and  $T(t)$ , from a reduced and representative group of input data.

We decided to use two different simulation programs; namely, Matlab/Simulink (from MathWorks) and Saber (Analog). Matlab/Simulink is used to study different control techniques related to the transient and steady state of a SRM drive as well as different techniques for ripple-torque minimization, acoustic noise minimization, etc. Saber is mainly used to analyze different convert topologies, switching techniques, switching loses, efficiency, etc. Both programs allow simulation of a closed-loop system.

The typical SRM is a double-salient, single-phase-excited motor structure in which both the rotor and stator have salient poles. Usually only the stator carries windings providing the necessary excitation.

The stator is excited through a power converter where the control of the power switches is made by taking into account the rotor position. Therefore, the modeling of a SRM drive involves three different components: the electromechanical system (the SRM), the power electronics (the power converter) and the control algorithms (the control block or controller).

Unfortunately, there is not a unique SRM model because the task of defining a relationship for the flux linkages is complex due to the high degree of magnetic saturation, which result in a severe non-linearity in the expressions relating flux linkages, current and rotor position. Consequently, different modeling techniques were analyzed. In general, the models of SRM can be classified by the technique used to handle the non-linearity of the relationship between the flux linkages and the current (as a function of rotor position). From an analysis of the relevant literature, two modeling techniques were selected. The first technique uses the cubic spline interpolation to obtain the flux-linkage characteristic; this technique is very accurate but time consuming. The second technique uses an ultra-fast model of the SRM. High accuracy is achieved after calibration of this model using data obtained through finite-element analysis or measurements. The two different simulation techniques were implemented in Matlab/Simulink. A comparison of these techniques is still performed at the time of writing this report.

### Present Research Activities

At the writing of this report, the following activities are in progress:

- The evaluation of the different SRM topologies. We are presently analyzing the 10/8 SRM topology. A disadvantage of the ANSYS-based field solutions is that to perform one torque cycle for the different topologies and excitation cases (i.e., single- or multi-phase excitation) take considerable amount of computing time. We are interacting with Dr. Selvam from the Department of Civil Engineering in order to develop a finite-element technique which will allow to speed up the finite-element simulations; this technique should replace ANSYS as the finite-element simulation tool. Dr. Selvam has extensive experience in performing finite-element analysis of systems having 1 million nodes.
- The development of the Matlab/Simulink program to simulate the closed-loop operation of a SRM drive. This program will allow us to start working on the control algorithms.
- The development of the Saber input data file to simulate the closed-loop operation of a SRM drive.
- The evaluation of different SRM modeling techniques for SRM having multi-phase excitation.
- Training on the TMS320C240 digital signal processor from Texas Instruments.
- The AHB and C-dump power converters are mainly suitable for single-phase excited SRMs. Multi-phase excitation can contribute to torque production, which it is very important for EV applications; e.g., 20-30% more torque can be produced. Multi-phase excitation requires the use of a VSI, which is mature and has been used extensively in the industry. During the Summer 1999 we will explore the feasibility of applying a three-phase VSI to control a 6/4 SRM available in our laboratory in order to gain practical experience in controlling SRMs. We will be using the TMS320C240 DSP to implement the controller.

### Grant Expenditures

The following expenditures have taken place since August 1, 1998 until May 15, 1999:

Salaries:	
J. C. Balda	\$ 1,265.66
T. W. Martin	\$ 10,210.22
Graduates	\$ 19,110.00
Total Salaries	\$ 30,585.88

Fringe Benefits:	
Faculty and Graduate Students	\$ 409.44

Tuition \$ 6,254.00

Total Expenditures \$ 37,249.32

Graduate students are paid \$ 910 per month plus their tuition (\$ 161.00 per credit hour). Paying of their tuition is required by University policy for those graduate students on half-time appointments (the other 50% are for their studies). Fringe benefits are 0.5% for graduate students and 24.8% for faculty members.

#### References

- [1] S. Ramamurthy, J. C. Balda, T. W. Martin, The Power Rating of an Electric Motor for Electric Vehicles (Task (a)), Report 1.1 submitted to the Office of Naval Research.

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